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Substrate Materials Used in Microchip Gas Chromatography

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Abstract

Although silicon-glass hybrid systems have been most commonly used to fabricate microchip columns for miniaturized gas chromatography (GC), a variety of other materials have been investigated. These include all-glass microchips, various polymers alone or in combination, and different metal substrates. This review gives an overview of the different substrates used in making microchip GC columns, and provides a discussion of their advantages and disadvantages for use in microchip fabrication and separation performance.

Keywords: Gas Chromatography, Microship, Microfabrication, Substrate, Miniaturized GC.

1. Introduction

The widespread applicability of gas chromatography (GC) has generated significant recent interest in development of miniaturized and hand-portable systems. Such instruments are advantageous over bench-top instruments for applications in which it is desirable to move the instrument around the laboratory, place it in close proximity to other instruments, position it next to a process stream or batch manufacturing system for monitoring, or take it out of the laboratory for on-site or point-of-care analysis[1]. As is well known, the most critical component of the GC is the column in which the separation takes place.

Since 1979, with the introduction of the first silicon microchip column by Terry et al.[2], there has been tremendous interest among researchers in fabricating microchip GC columns in planar substrates[3] in contrast to using fused silica open tubular capillary columns, which, interestingly, were also first reported[4] in the same year (i.e., 1979). The first attempt to fabricate a microchip GC column in a substrate other than silicon was reported by Noh et al.[5] in 2002, for which they used parylene C [poly(monochloro-p-xylene)]. The popular GC stationary phase polymer, polydimethylsiloxane or PDMS, was investigated as a microchip GC substrate several years later by Malainou et al.[6]. Another polymeric material that was investigated for use as a disposable microchip column substrate was silane-doped epoxy[7]. A substantially monolithic structure formed from green-sheet ceramic layers sintered together was proposed by Briscoe et al.[8] without showing any results; however, in 2013, Darko produced several ceramic columns as part of his master's thesis[9] and analyzed mixtures of normal hydrocarbons and BTEX. Subsequently, in the same year, he coauthored a report[10] on the novelty of the ceramic platform in microchip GC.

The viability of using metal as a substrate for microchip GC was first investigated by Bhushan et al.[11] in 2004. The reasons that prompted such investigation

included column (i.e., microchip) robustness and ability to accommodate high temperatures[12,13]. While Bhushan et al. used nickel as substrate, other metals, such as stainless steel[14,15] and titanium[16] were investigated by other researchers. It is worth mentioning here that the vast majority of microchip columns that have been reported have been etched in silicon and anodically bonded to a top glass cover[3]. An all-glass microchip GC column was first reported by Halliday et al.[17] in 2010 and later explored to a limited extent by other researchers[18].

Although remarkable progress has been made in micromachining that has allowed the etching of channels in a variety of planar substrates[3,19], the search for an ideal substrate still continues among researchers. There are several reasons and motivations behind this; for instance, silicon may seem to be ideal because of its established micromaching technology and its similarity to fused silica capillary columns in terms of surface chemistry. However, the currently used method of connecting the microchip to inlet and outlet capillary leads for interfacing to injector and detector, i.e., using adhesives, is prone to leakage and cannot be exposed to high temperatures[20,21]. All-glass substrates are seldom used because the active surface leads to peak tailing for polar analytes, similar to what was experienced years ago with glass open tubular columns, and glass exhibits poor heat conductivity[3].

Unfortunately, there is no perfect material identified to date to use as substrate for microchip GC. This review explores the different substrates that have been reported for microchip GC column technology, and emphasizes their advantages and disadvantages.

2. Substrate Materials

2.1. Silicon

Silicon has the distinction of being the substrate used for the first ever microfabricated analytical device[22], which just happened to be a microchip GC column. It was fabricated by Terry et al.[2] in 1979 (Figure 1). The motivation was to create a lightweight, rugged, portable GC system for the exploration of

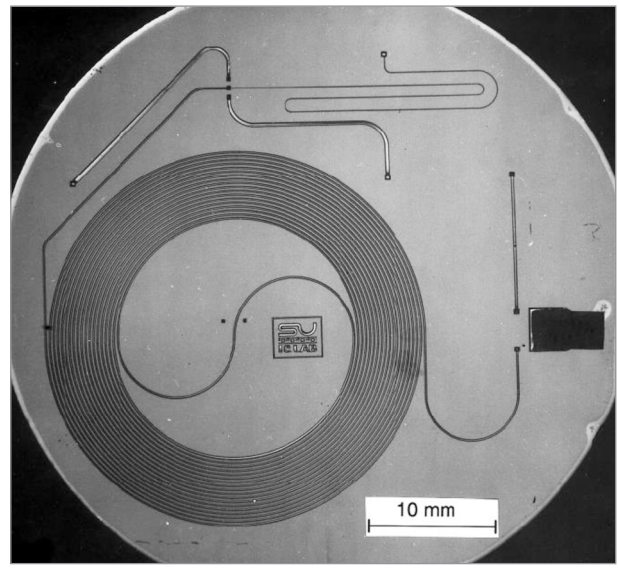

Figure 1. Photograph of the first microfabricated silicon column on a 5 cm silicon wafer with other integrated components[22]. Reproduced with permission from the Royal Society of Chemistry.

Mars by NASA[23]. Since then, silicon continues to be the most popular substrate[3] in which to micromachine channels for microchip GC columns. Figure 2 shows the dominance of silicon in comparison to other substrates. There are many advantages of silicon substrates:

(1) They can be fabricated precisely in batches using already established semiconductor micromachining technology[24].

(2) Silicon is mechanically stable and resistant to most chemicals and organic solvents.

(3) There are various bonding techniques available to cover etched silicon microchannels with silicon or glass plates to form a hermetically sealed device[25].

(4) The well-established silanol (Si-OH) surface chemistry that is key to fabrication of high-performance capillary GC columns can be easily modified and implemented for silicon microchannels[3].

(5) Silicon also provides low thermal mass, uniform thermal distribution, and high thermal conductivity[26]. These thermal features are extremely attractive because temperature is the most important programming variable in GC.

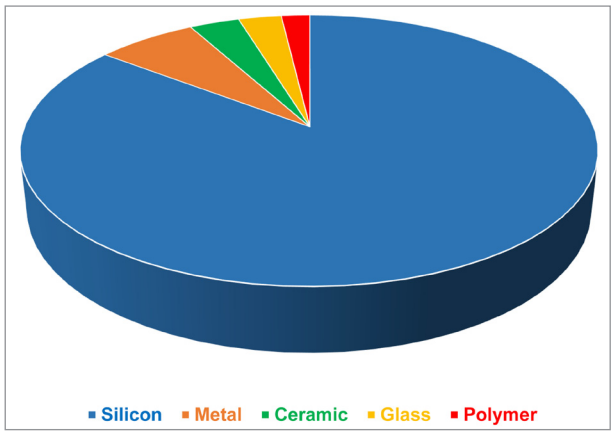

Figure 2. Comparison of substrate materials used in microchip fabrication. Recreated from Ref. 3.

Fabrication of silicon microchip GC columns follows the well-established procedures of wet and dry etching[19]. Etching is the process by which material is chemically removed from its surface. By using etching techniques, channels with different column geometries and holes can be produced in the silicon wafers. Wet etching is the simplest type of etching and has been used in semiconductor processing since the early 1950's, and essentially consists of immersing the substrate in a liquid chemical or mixture of chemicals which eat away any exposed surfaces to form soluble by-products.There are two main options for wet etching of silicon: isotropic and anisotropic. In isotropic etching, hydrofluoric (HF), nitric (HNO_3) and acetic acids (CH_3COOH) are used, and etching occurs in all crystallographic directions at the same rate to remove exposed substrate material and some material under the mask[26]. In anisotropic or orientation dependent etching, a chemical such as KOH attacks silicon preferentially in a plane, producing a characteristic anisotropic V-etch[27]. Other anisotropic wet etchants include ethylene diamine pyrocatechol and tetramethylammonium hydroxide[28]. The residue deposition from KOH etching of Si is typically regarded as a disadvantage of this technology[29].

As an alternative to wet etching, channels in silicon wafers can also be created by dry etching, which does not involve liquid chemicals. It is a widely used process since it is easier to control and is capable of defining precise features smaller than 100 nm. However, the main purpose of dry etching is to generate anisotropic etch profiles. In the dry etch process, material is removed by reactive gases or plasmas, physical sputtering and ion beam-induced etching, or by a combination (reactive ion etching). The most popular dry etching process used in GC microchip fabrication is deep reactive-ion etching (DRIE). This method usually consists of two alternating cycles: etching and passivating. During etching, shallow isotropic trenches are formed in the silicon substrate with SF_6. However, during passivation, a Teflon-like protective fluorocarbon film is deposited on the trench walls using C_4H_8 gas. In the subsequent etching cycle, ion bombardment promotes the preferential removal of the film from all horizontal surfaces, creating highly anisotropic features[30].

The etched silicon wafer is bonded to another plate (typically silicon or glass) to create a sealed GC column. Surface properties and cleanliness significantly influence the process. The presence of any particles on the bonding surface usually leads to bonding failure. The most common bonding procedure used for silicon microfabricated GC columns is silicon/glass anodic bonding, in which a Pyrex glass top is placed on top of the silicon wafer, enclosing the microchannel[3]. Since both glass and silicon remain rigid during the process, it is possible to bond glass to a silicon surface without affecting the features[31]. In this process, the two wafers are held together on a hot plate (300–450°C) and a high DC voltage (400–1000 V) is applied to the pair such that the glass becomes negative with respect to the silicon. During the process, alkali cations in the glass are depleted from the vicinity of the anode and transported toward the cathode. For most glasses used for anodic bonding, conduction is primarily realized by Na^+ ions and, to a lesser extent, by K^+ ions. As the Na^+ and K^+ions are displaced toward the cathode, they leave an alkali-depleted region near the anode with negative (O_2^-) space charge at the interface. This depletion region generates a large electric field between the silicon and Pyrex wafers, and they are pulled together where oxygen combines

with silicon to form irreversible Si-O-Si bonds (SiO_2 film) between the silicon and glass substrates[32,33].

Other than anodic bonding, silicon microchip fabrication can also utilize various fusion bonding techniques. Yu[34] first used this in fabricating an all-silicon 5.6 m column in a 3-in. silicon wafer. In fusion bonding of silicon, two oxidized silicon wafers are first weak bonded at room temperature, followed by annealing at 1,100 °C. Wang et al.[21] reported silicon-to-silicon fusion bonding to produce columns up to 2.7 m long. Ghosh et al.[20] also reported a 5.9 m long microchip column that was fusion bonded. In addition to silicon-to-silicon fusion bonding, glass covers could also be bonded to silicon[35]. Gold diffusion bonding was used by Radadia et al. for fabricating an all-silicon microchip GC column[36]. In this process, a bonding layer of eutectic alloy such as gold (Au) was formed at the interface at a specific temperature[37]. Navaei et al.[38] used eutectic fusion bonding of silicon to silicon in fabricating a 3 m microchip column. Eutectic diffusion bonding is much more forgiving to surface flatness, deformities and contamination compared to direct fusion bonding of silicon to silicon[39].

The demerits of silicon-glass microchips arise from the fact that when a glass cover is bonded to an etched silicon wafer, there can be mismatch of thermal properties of the two materials, resulting in uneven heating and expansion. This can be avoided by fabricating all-silicon microchips. Another problem that limits the applicability of both silicon-glass and all-silicon microchips is the adhesive-based interfacing that is typically used to connect capillary tubes to the chip for sample introduction and detection. As most of the adhesives are unstable at high temperature and have significantly different coefficients of thermal expansion (CTE) compared to silicon and glass, leakage tends to develop after thermal cycling[20]. Although there are reports of compression-based interfacing[20,40] that overcomes this problem to some extent, most interfacing continues to utilize adhesives[3]. Furthermore, it is very difficult to minimize dead volumes at the interfacing when using adhesives. Another characteristic that is often overlooked is that silicon microchips are brittle at high temperature, which is disadvantageous for portable instrumentation. On the positive side, because of the similarities between an oxidized silicon surface and a fused silica capillary surface, a well-deactivated and coated silicon microchip is expected to provide comparable analytical performance. Although there are encouraging reports, nonetheless, the full potential of silicon microchip GC columns is yet to be realized due to issues related to interfacing, dead volumes and uniform coating.

2.2. Glass

In contrast to silicon, which is opaque and conductive, glass is optically transparent and electrically insulating. Quartz and borosilicate glass (Pyrex) wafers have found acceptance in CE and LC microchip technology[41,42]. However, in GC, their use has been limited[3]. As discussed in the previous section, the major exception is that glass is used extensively in silicon-glass hybrid columns where the channel is etched into the silicon surface, followed by anodic bonding of a glass cover plate. As a material, glass can be advantageous[3,43] for the following reasons:

(1) The use of glass is economical.

(2) Glass is chemically resistant to many chemicals and solvents.

(3) Glass has silanol surface chemistry similar to silica.

(4) Glass is not permeable to the carrier gas.

(5) Micromachining of glass is similar to the well-established technology for silicon.

However, fewer examples exist for glass fabrication than for silica most likely because glass dopants and metal oxide impurities lead to analyte adsorption and peak tailing. The poor heat conductivity of glass is also a disadvantage in microchip GC. Other

disadvantages include lower fabrication yield, often due to unpredictable surface conditions, and irreproducible bonding quality[3]. The first microchip GC column in glass was reported by Lewis et al.[44]. Usually, glass is patterned with methods coming from the semiconductor industry using photolithography. During fabrication, polished glass surfaces are coated with an adhesion layer of titanium or chromium before application of a photoresist with the desired pattern. The light-sensitive photoresist is exposed to light to uncover the glass surface for etching. Common isotropic etchants for glass are hydrofluoric acid alone or in buffered form (HF/NH_4F)[45]. On the other hand, dry etching techniques can generate an anisotropic profile on glass, using a variety of etchants: C_3F_8, CHF_3, CF_4/CHF_3, SF_6/Ar, SF_6, CF_4/O_2 and CF_4/Ar[46].

Microchip columns fabricated by Lewis et al.[44] used two glass (Schott B270) wafers (one 0.5 mm thick, the second 2.5 mm thick) with a channel chemically etched (HF) in the thicker wafer, and the thinner wafer bonded on top to form an enclosed column. A cold bonding technique that relies on the flatness/smoothness of the surface and van der Walls forces was used to hermetically seal the chip. Chips fabricated in this manner could withstand pressures up to 50 bar. Figure 3 shows a microchip column fabricated in glass[47].

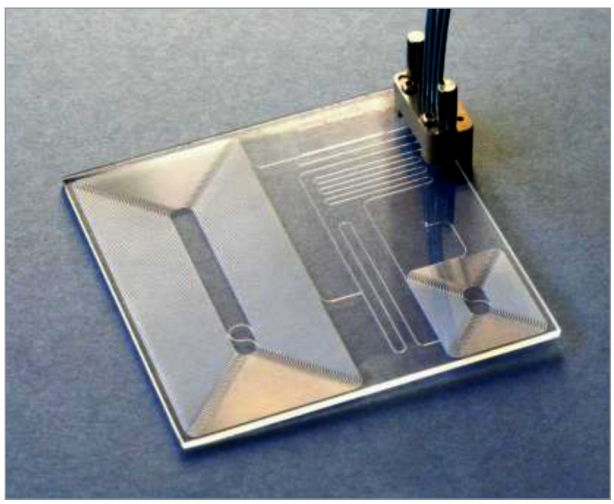

Figure 3. A 100 mm x 100 mm glass microchip with fluidic connector[47]. Reproduced with permission from Dolomite Microfluidics, UK.

Qin and Gianchandani[18,48] reported several borosilicate glass microchip columns for integrated systems that were fabricated using micro abrasive jet machining (sand blasting). Sand blasting is known to be an economical way of microfabricating substrates such as glass or silicon. In this process, a mask containing patterned holes for the desired geometry is placed over the substrate. Next, a beam of compressed air containing fine grains of silicon carbide is directed towards the mask, which removes material from the exposed surface[45]. The sand blasted features typically have a 22° taper and a corner radius of 125 µm. In this study[18], the channels were enclosed using an adhesive bonding technique. Adhesive bonding is a simple, robust, low-cost bonding procedure used to bring two surfaces together with the help of an intermediate layer. Polymers, glass, photoresists and polyimides are some of the materials suitable for intermediate bonding layers[26]. An epoxy photoresist, SU-8, was spin-coated over the microfabricated separation channel, which smoothed the sand blasted surface and also served as an adhesion layer. An adhesion promoter was used for better sealing. Once the two parts were aligned and compressed together, a series of soft baking steps at 150 °C and 95 °C were followed by exposure to UV radiation and hard baking at 150 °C.

Sun et al.[49] fabricated a silicon/glass packed column where channels were etched into both the silicon and glass plates using a laser. During laser etching, a photochemical reaction occurred within the glass that created a high density of nanocrystals within the critically exposed volume. However, burrs were created on the edges due to laser ablation that caused difficulties in bonding. This was overcome by polishing the etched substrates before bonding.

Despite their similarities to silicon, few studies of glass microcolumns have been reported in the literature. While wet etching and sand blasting are simple methods for glass micromachining, wet etching is not precise due to isotropic etching behavior and sand blasting is limited

due to difficulty in creating small patterns because of low dry film resist resolution and large powder particle size[50]. On the other hand, properly deactivated fused silica/glass columns should produce column efficiencies comparable to fused silica open tubular columns, and the transparent nature of the glass can be helpful in tracking the solvent meniscus during static coating.

2.3. Ceramic

Low temperature co-fired ceramic (LTCC) is an aluminum oxide-based material that is processed in layers, assembled together, and then fired at elevated temperature[42]. This substrate has been recently used for microfabrication of lab-on-a-chip devices such as for capillary electrophoresis and liquid chromatography[51,52]. Some properties of ceramics that can be advantages in microchip GC fabrication include[10,45]:

(1) Ceramics possess high thermal and chemical stabilities.

(2) Ceramic microchips are suitable for applications in harsh environments (robustness).

(3) Fabrication of ceramic microchips can be low cost and rapid without the need for a clean room environment.

(4) The ceramic monolithic design eliminates the need for sealing.

The concept of a ceramic column in microchip GC was first introduced by Briscoe et al.[8] (US Patent US 6527890 B1) in 2004. However, it was not supported by any analytical data. In 2010, Adkins and Lewis[53] (US 2011/0226040 A1) also mentioned ceramic as a possible substrate among others in describing a "folded passage column" design that was formed by joining a first channel in a surface through a slot to a second channel in a second surface. However, the first ceramic microchip GC columns were fabricated by Darko[9] in 2013 using low temperature co-fired ceramic tiles and reported in his master's thesis. Microchips with various column lengths ranging from 0.1 m packed to 15 m open tubular were fabricated with C18 particles and PDMS coatings, respectively, as stationary phases. Although the possibility of using such substrates was demonstrated, chromatograms produced using the resultant microchip columns were not very impressive. For instance, a C8-C20 *n*-alkane mixture suffered from baseline rise even with moderate temperature programming (i.e., 45-210 °C at 5 °C/min), while a mixture containing compounds with various functional groups resulted in chromatograms exhibiting uneven baseline and poor peak shapes. The poor results were justified by claiming that such diminished chromatographic behavior was a result of poor coating procedure. For instance, when stationary phase was deposited onto the ceramic surface, it was speculated that much of the reactive oxide surface was left exposed, which would be eliminated with multiple layers of coating. Another disadvantage that can be anticipated with ceramic substrates is their high porosity and channel roughness, which may lead to cavitation during static coating.

Fabrication of ceramic microchips involves a four-step process: texturing, stacking, laminating and co-firing. Texturing can be done by various methods such as punching, embossing, laser cutting, etc. Darko et al.[10] patterned a 115 µm x 12.7 cm x 12.7 cm green unfired ceramic tile using an ultraviolet laser to machine the channel. A channel layer tape was then sandwiched between two capping tape layers of 250 µm thickness. The top layer had 100 µm through-holes that could be aligned with the inlet and outlet of the channel. The assembly was then laminated in a uniaxial press at 70°C to seal the layers together. The sealed unit was then placed in a box furnace for sintering at a temperature of 850 °C. Figure 4 shows a microchip GC column fabricated within a low-temperature cofired ceramic.

2.4. Metal

Capillary columns made from stainless steel, nickel and to a lesser extent copper have been in use for many years[54]. However, in the area of microchip GC, the use of metal substrates was initially investigated by Bhusan et al.[11]. They were concerned that the early

Figure 4. A 15 m long and 100 µm wide microchip column fabricated in a ceramic substrate[10]. Reproduced with permission from the American Chemical Society.

silicon-glass hybrid columns were limited primarily to isothermal operation because of high thermal capacitance that prevented them from being used with rapid temperature programming. Such column salso suffered from thermal expansion mismatch during temperature program cycling. They initially briefly reported the fabrication of nickel columns in 2004 using a combination of micromachining and electroplating. Other column materials were investigated in subsequent studies[14-16]. Metal columns are attractive primarily because of two reasons: their robustness and high temperature compatibility.

A unique microfabricated GC column using stacked nickel substrates was reported by Lewis and Wheeler[55] (US 7273517 B1) in 2005. Each planar substrate had a machined serpentine channel and a through-hole at the end of the channel, which connected to the channel in the following substrate, except for the top substrate that only had an inlet hole. In this design, a continuous channel (i.e., column) was formed from the inlet (i.e., top of the stack) to the outlet (i.e., bottom of the stack). A related design, called a "folded passage column" was put forward by Adkins and Lewis[53] (US 2011/0226040 A1) in 2010, for which metal was listed as a possible substrate. A metal microchip column based on this design is used in the portable gas chromatograph recently commercialized by Defiant Technologies[56]. The desire to make a rugged microchip column led to the investigation of stainless-steel as a substrate by Iwaya et al.[15]. In 2012, they reported the fabrication of columns approximately 3 m in length fabricated in stainless-steel. Thurbide and co-workers[9,16] investigated the use of titanium tiles as a substrate material for microchip GC columns. They fabricated 0.1 m packed and 5 to 15.0 m open channels in 2013 and 2017. Even though one of the primary goals of the metal microchip columns was to separate nonvolatile analytes that required high temperature, it wasn't until 2018 that Ghosh et al.[14] and Lee et al.[57] first reported the use of a 10 m long statically coated stainless-steel microchip column for the separation of semi-volatile compounds at temperatures up to 350 °C. Figure 5 shows a 10 m x 120 µm x 60 µm stainless steel metal microchip column[14].

The LIGA technique was used by Bhushan et al.[12,13] for fabricating metal microchip columns. LIGA is a German acronym consisting of LI (lithographie for lithography), G (galvanik for electroplating) and A (abfonnung for replication technique, such as molding).The LIGA technique reported by the authors was based on X-ray lithography using synchrotron radiation. The mask consisted of a 2 µm thick silicon nitride membrane with approximately 10 µm thick gold absorber. X-ray sensitive polymethylmethacrylate was used as a resist material. To produce 0.5 and 2 m long nickel columns, silicon wafers were used as sacrificial substrate on which a layer of titanium was grown. Next, a polymethylmethacrylate wafer was bonded to it and exposed to X-rays. The exposure caused bonds to break in exposed areas of the polymethylmethacrylate, but remain intact in unexposed areas under the mask. When placed

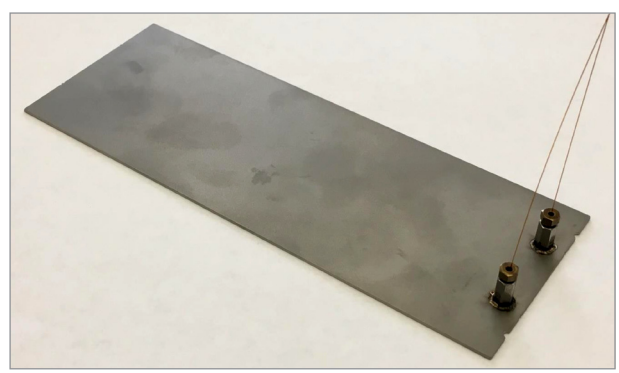

Figure 5. A 10 m x 120 µm x 60 µm stainless steel microchip column[14].

in a chemical developer, the exposed areas were washed away, creating a pattern in the polymethymethacrylate. Next, Nickel was electrodeposited on the top of the polymethylmethacrylate mold, and then over-plated and polished. Then the silicon wafer was completely wet-etched from the bottom and sealed with another layer of electrodeposited nickel. Finally, the polymethylmethacrylate was removed by heat to create a high aspect ratio channel. LIGA was also used by Lewis and Wheeler[55] for fabrication of microchip GC columns by connecting an array of vertical channels in planar nickel substrates.

Fabrication of stainless-steel columns by Iwaya et al.[15] involved 0.5 mm thick stainless-steel plates that were wet-etched to generate a semi-circular cross section. Then, the two plates were bonded together by diffusion. A proprietary method was used to etch channels in stainless steel substrates as reported by Ghosh et al.[14], that involved stacked layers that were also diffusion bonded to create a hermetically sealed microchip. Electrochemically etched titanium tiles were first evaluated as substrates for microchip columns (0.1 to 15 m) by Darko[9] in 2013. In 2017, Raut and Thurbide[16] also investigated the potential use of titanium tiles by reporting a 7.5 cm x 15 cm rectangular monolithic device that contained 5 m x 100 µm wide channels. In both cases, diffusion bonding at elevated temperature was used.

The demerits of metal columns arise from the fact that, compared to other substrates, fabrication in metal is cumbersome and can be very expensive. Metal surfaces also require additional deactivation, such as vapor deposition of silicon, to mask the reactive sites.

2.5. Polymeric

Organic polymers have been extensively investigated for microfluids in the last two decades. The availability of different polymeric materials with diverse properties, such as mechanical stability, thermal characteristics, surface chemistry, etc., make them attractive for fabrication of microchip devices. They are advantageous because of the following reasons[25,42]:

(1) Fabrication of microchips from polymers is inexpensive.

(2) Microchips from polymers are amenable to mass production (hot embossing, molding, etc.).

(3) Polymeric microchips can be designed such that they do not absorb water.

The first polymeric microfabricated GC columns were reported by Noh et al.[5] in 2002. In their work, 100 µm wide x 350 µm deep microchannels were etched into silicon wafers. A 5 µm thick parylene layer was deposited over the channels, followed by sputtering a 1 µm thick platinum layer over the parylene layer. Finally, another layer of parylene was deposited over the top of the platinum layer. The metal film was added for two reasons: (1) to reduce gas permeability of the parylene in order to prevent oxidation of the stationary phase and (2) to aid uniform distribution of heat. A parylene-coated Pyrex glass plate was compression bonded to seal the column hermetically. After bonding, the silicon wafer was wet-etched, leaving a free-standing parylene column.

Malainou et al.[6] reported the fabrication of a microchip GC column made from poly(dimethylsiloxane), i.e., PDMS, by casting in a mold. The mold was formed from a photosensitive SU-8 resist, which was spun on a silicon wafer and patterned. A solution of PDMS was cast over the mold and thermally cured to produce the elastomer substrate. Finally, a PMMA plate covered with liquid PDMS was used for sealing. MacNaughton et al.[58,59] also reported an on-chip gas analysis system using a PDMS microchip column for both structural and functional purposes, which the authors believed would be advantageous (Figure 6) because it eliminated the tedious process of coating the microchip channels. The channels were formed by standard micro molding with SU-8 photoresist on a silicon wafer and sealed with a glass wafer. Before sealing, both the glass wafer and

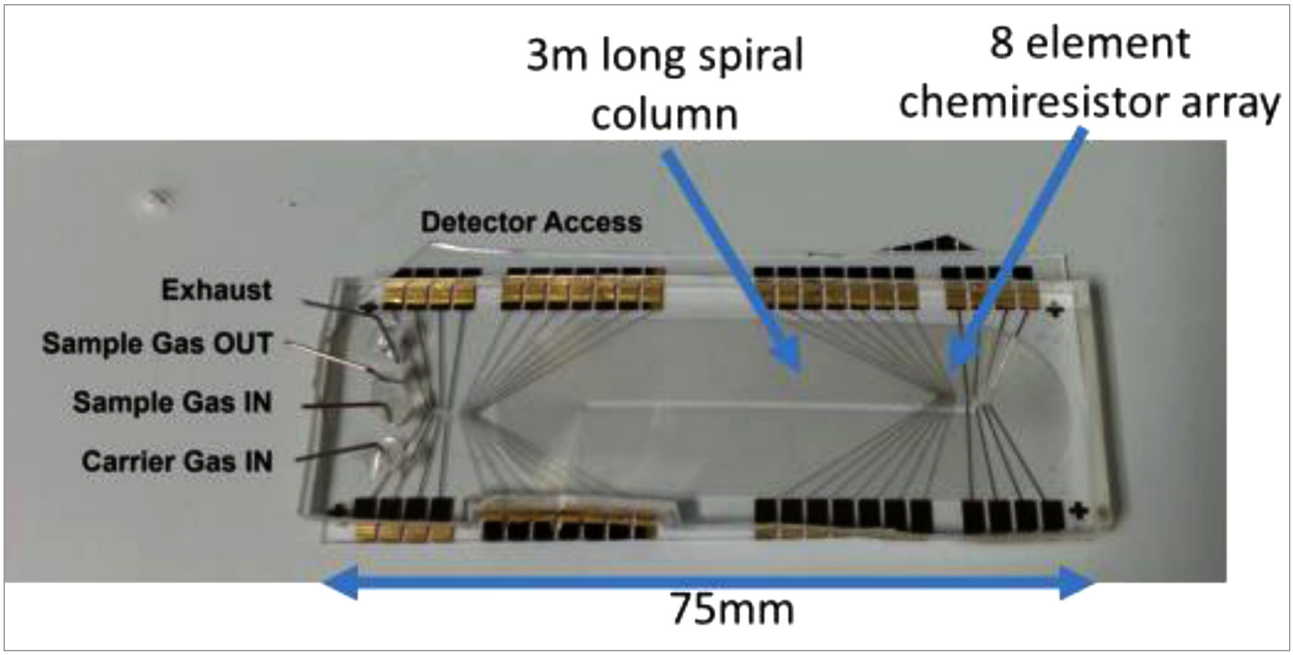

Figure 6. Microchip column on a PDMS substrate (by permission of the authors, Ref. 59).

micro molded PDMS channels were modified using an oxygen plasma to facilitate irreversible covalent bonding.

Rankin and Suslick[7] reported a disposable GC microchip column fabricated by polymer replication from a reusable mold. The polymer was a combination of an organosilane mixed with epoxy. The reusable mold was made out of polychlorotrifluoroethylene with negative relief. The microchip columns were produced by casting a thermoset prepolymer into the mold, degassing under vacuum and curing. After curing, the imprinted pieces were removed from the mold, sealed with a bottom layer of partially cured thermostat polymer and cured again. The authors suggested that an ideal polymer microcolumn could be made out of a polymer that self-segregates into permeable and impermeable surfaces. Therefore, 10 wt% diethoxydimethylsilane was doped with epoxy to create phase separation and surface segregation upon curing. The authors proposed that the siloxane-rich domain acted as a stationary phase and the epoxy polymer served as a structural material.

Although various possibilities for fabrication of microchip columns out of polymers have been reported, the chromatographic performance of such columns has not been impressive. Again, polymers like PDMS are permeable to gas, which can lead to stationary phase degradation by oxygen in the air. The major limitation of PDMS for GC is its relatively low upper temperature limit (usually below 200 °C).

3. Conclusions

Microchip columns fabricated from various substrates have certainly offered an alternative to fused silica capillary columns; however, the performance of such columns generally do not match the high performance of conventional open tubular capillary columns. A careful choice of substrate, along with improvements in interfacing, dead volume reduction and uniform stationary phase deposition will be important for further advancement and ultimate adoption of this technology.

References

[1] E. Lussac, R. Barattin, P. Cardinael, V. Agasse, Review on Micro-Gas Analyzer Systems: Feasibility, Separations and Applications, Crit Rev Anal Chem 46(6) (2016) 455-468.

[2] S.C. Terry, J.H. Jerman, J.B. Angell, Gas-Chromatographic Air Analyzer Fabricated on a Silicon-Wafer, IEEETrans Electron Dev 26(12) (1979) 1880-1886.

[3] A. Ghosh, C.R. Vilorio, A.R. Hawkins, M.L. Lee, Microchip Gas Chromatography Columns, Interfacing and Performance, Talanta 188 (2018) 463-492.

[4] R.D. Dandeneau, E.H. Zerenner, An investigation of Glasses for Capillary Chromatography, J High Res Chrom 2(6) (1979) 351-356.

[5] H.S. Noh, P.J. Hesketh, G.C. Frye-Mason, Parylene Gas Chromatographic Column for Rapid Thermal Cycling, J Microelectromech Sys. 11(6) (2002) 718-725.

[6] A. Malainou, M.E. Vlachopoulou, R. Triantafyllopoulou, A. Tserepi, S. Chatzandroulis, The Fabrication of a Microcolumn for Gas Separation Using Poly(dimethylsiloxane) as the Structural and Functional Material, J Micromech Microeng 18(10) (2008), 1-6.

[7] J.M. Rankin, K.S. Suslick, The Development of a Disposable Gas Chromatography Microcolumn, Chem Commun 51(43) (2015) 8920-8923.

[8] H.Y. Cynthia G. Briscoe, Grodzinski, Rong-Fong Huang, Jeremy W. Burdon, Multilayered Ceramic Micro-Gas Chromatograph and Method for Making the Same, US Patent US 6527890 B1,(2003).

[9] E. Darko, Charecterization of Novel Materials as Platforms for Performing Microflidic Gas Chromatography, University of Calgary, Thesis, (2013).

[10] E. Darko, K.B. Thurbide, G.C. Gerhardt, J. Michienzi, Characterization of Low-Temperature Cofired Ceramic Tiles as Platforms for Gas Chromatographic Separations, Anal Chem 85(11) (2013) 5376-5381.

[11] A. Bhushan, D. Yemane, J. Goettert, E.B. Overton, M.C. Murphy, Fabrication and Testing of High Aspect Ratio Metal Micro-Gas Chromatograph Columns, ASME 2004 Int Mech Eng Cong and Expo, Am Soc of Mech Engineers, (2004), 321-324.

[12] A. Bhushan, D. Yemane, E.B. Overton, J. Goettert, M.C. Murphy, Fabrication and Preliminary Results for LiGA Fabricated Nickel Micro Gas Chromatograph Columns, J Microelectromech Sys 16(2) (2007) 383-393.

[13] A. Bhushan, D. Yemane, D. Trudell, E.B. Overton, J. Goettert, Fabrication of Micro-Gas Chromatograph Columns for Fast Chromatography, Microsyst Technol 13(3-4) (2007) 361-368.

[14] T. Iwaya, S. Akao, T. Sakamoto, T. Tsuji, N. Nakaso, K. Yamanaka, Development of High Precision Metal Micro-Electro-Mechanical-Systems Column for Portable Surface Acoustic Wave Gas Chromatograph, Jpn J Appl Phys 51(7) (2012), 07GC24-1-07GC246.

[15] A. Ghosh A. R. Foster, C.R. Vilorio, L. T. Tolley, A. R. Hawkins, B.D. Ivesron, H.D. Tolley, M. L. Lee, Effect of Thermal Control in Microchip Thermal Gradient Gas Chromatography, Oral Presentation, Pittcon, (2018).

[16] R.P. Raut, K.B. Thurbide, Characterization of Titanium Tiles as Novel Platforms for Micro-Flame Ionization Detection in Miniature Gas Chromatography, Chromatographia 80(5) (2017) 805-812.

[17] J. Halliday, A.C. Lewis, J.F. Hamilton, C. Rhodes, K.D. Bartle, P. Homewood, R.J.P. Grenfell, B. Goody, A. Harling, P. Brewer, G. Vargha, M.J.T. Milton, Lab-on-a-Chip GC for Environmental Research, LC GC Eur 23(10) (2010) 514-523.

[18] Y.T. Qin, Y.B. Gianchandani, iGC1: An Integrated Fluidic System for Gas Chromatography Including Knudsen Pump, Preconcentrator, Column, and Detector Microfabricated by a Three-Mask Process, J Microelectromech Sys 23(4) (2014) 980-990.

[19] V.N. Sidelnikov, O.A. Nikolaeva, I.A. Platonov, V.N. Parmon, Gas chromatography of the Future: Columns Whose Time has Come, Russ Chem Rev 85(10) (2016) 1033-1055.

[20] A. Ghosh, J.E. Johnson, J.G. Nuss, B.A. Stark, A.R. Hawkins, L.T. Tolley, B.D. Iverson, H.D. Tolley, M.L. Lee, Extending the Upper Temperature Range of Gas Chromatography with All-Silicon Microchip Columns Using a Heater/Clamp Assembly, J Chromatogr A 1517 (2017) 134-141.

[21] A.Z. Wang, S. Hynynen, A.R. Hawkins, S.E. Tolley, H.D. Tolley, M.L. Lee, Axial Thermal Gradients in Microchip Gas Chromatography, J Chromatogr A 1374 (2014) 216-223.

[22] A. de Mello, FOCUS On-chip Chromatography: The Last Twenty Years, Lab Chip 2(3) (2002) 48N-54N.

[23] S.C. Terry, A Gas Chromatography System Fabricated on a Sillicon Wafer Using Integrated Circuit Technology, Stanford Univesity, Dissertation,(1975).

[24] L.Csepregi, Micromechanics: A silicon Microfabrication Technology, Microelec Eng 3(1-4) (1985) 221-234.

[25] C. Vollrath, P.S. Dittrich, MIcrofluidics:Basic Concepts and Microchip Fabrication, N. Bontoux, L. Dauphinot, M-C. Potier (Ed.), Unravelling Single Cell Genomics: Micro and Nanotools, Royal Soc of Chem (2010), 11-149.

[26] C. Iliescu, H. Taylor, M. Avram, J.M. Miao, S. Franssila, A Practical Guide for the Fabrication of Microfluidic Devices Using Glass and Silicon, Biomicrofluidics 6(1) (2012), 016505-1-016505-16.

[27] K.E. Bean, Anisotropic Etching of Silicon, IEEE Trans Electron Dev 25(10) (1978) 1185-1193.

[28] S. Dutta, M. Imran, P. Kumar, R. Pal, P. Datta, R. Chatterjee, Comparison of Etch Characteristics of KOH, TMAH and EDP for Bulk Micromachining of Silicon (110), Microsyst Technol 17(10-11) (2011) 1621-1628.

[29] H. Lu, H. Zhang, M.L. Jin, T. He, G.F. Zhou, L.L. Shui, Two-Layer Microstructures Fabricated by One-Step Anisotropic Wet Etching of Si in KOH Solution, Micromachines-Basel 7(19) (2016), 1-7.

[30] A.A. Ayon, K.S. Chen, K.A. Lohner, S.M. Spearing, H.H. Sawin, M.A. Schmidt, Deep Reactive Ion Etching of Silicon, Mater Res Soc Symp P 546 (1999) 51-61.

[31] K.B.Albaugh, D.H. Rasmussen, Mechanisms of Anodic Bonding of Silicon to Pyrex® Glass, IEEE Technical Digest on Solid-State Sensor and Actuator Workshop, IEEE, Hilton Head Island, SC, USA, (1988), 109-110.

[32] A.C.Lapadatu,.K. Schjølberg-Henriksen, Anodic Bonding, P. Ramm, J Jian-Qiang Lu, M. M. V. Taklo(Ed.), Handbook of Wafer Bond (2012), 63-80.

[33] C.C. Tripathi, S. Jain, P. Joshi, S.C. Sood, D. Kumar, Development of Low Cost Set Up for Anodic Bonding and its Characterization, Indian J Pure Ap Phy 46(10) (2008) 738-743.

[34] C.M. Yu, High performance hand-held gas chromatograph, (1998). https://www.osti.gov/biblio/304615.

[35] C.Y. Lee, C.C. Liu, S.C. Chen, C.M. Chiang, Y.H. Su, W.C. Kuo, High-performance MEMS-Based Gas Chromatography Column with Integrated Micro Heater, Microsyst Technol 17(4) (2011) 523-531.

[36] A.D. Radadia, A. Salehi-Khojin, R.I. Masel, M.A. Shannon, The Fabrication of All-Silicon Micro Gas Chromatography Columns Using Gold Diffusion Eutectic Bonding, J Micromech Microeng 20(1) (2010), 1-7.

[37] Z. Cui, Wafer Bonding, in: D. Li (Ed.), Encyclo of Microfluid and Nanofluid, Springer, Boston, MA, (2008).

[38] M. Navaei, A. Mahdavifar, J. Xu, J.D. Dimandja, G. McMurray, P.J. Hesketh, Micro-Fabrication of All Silicon 3 Meter GC Columns Using Gold Eutectic Fusion Bonding, Ecs J Solid State Sc 4(10) (2015) S3011-S3015.

[39] V. Dragoi, E. Cakmak, E. Pabo, Metal Wafer Bonding for MEMS Devices, Rom J Inf Sci Tech 13(1) (2010) 65-72.

[40] D. Gaddes, J. Westland, F.L. Dorman, S. Tadigadapa, Improved Micromachined Column Design and Fluidic Interconnects for Programmed High-Temperature Gas Chromatography Separations, J Chromatogr A 1349 (2014) 96-104.

[41] J.P. Grinias, R.T. Kennedy, Advances in and Prospects of Microchip Liquid Chromatography, Trend Anal Chem 81 (2016) 110-117.

[42] P.N. Nge, C.I. Rogers, A.T. Woolley, Advances in Microfluidic Materials, Functions, Integration, and Applications, Chem Rev 113(4) (2013) 2550-2583.

[43] K.N. Ren, J.H. Zhou, H.K. Wu, Materials for Microfluidic Chip Fabrication, Accounts Chem Res 46(11) (2013) 2396-2406.

[44] A.C. Lewis, J.F. Hamilton, C.N. Rhodes, J. Halliday, K.D. Bartle, P. Homewood, R.J.P. Grenfell, B. Goody, A.M. Harling, P. Brewer, G. Vargha, M.J.T. Milton, Microfabricated Planar Glass Gas Chromatography with Photoionization Detection, J Chromatogr A 1217(5) (2010) 768-774.

[45] R Knitter, T. R. Dietrich, Microfabrication in Ceramics and Glass, N. Kockmann (Ed.), Advanced Micro and Nanosystems, WILEY-VCH, Weinheim, (2006), 353-385.

[46] J.H. Park, N.E. Lee, J. Lee, J.S. Park, H.D. Park, Deep Dry Etching of Borosilicate Glass Using SF6 and SF6/Ar Inductively Coupled Plasmas, Microelectronic Engineering 82(2) (2005) 119-128.

[47] Miniaturization of a Gas Chromatography Equipment for Enviromental Testing. https://www.dolomite-microfluids.com/support/downloads/

[48] Y.T. Qin, Y.B. Gianchandani, iGC2: An Architecture for Micro Gas Chromatographs Utilizing Integrated Bi-Directional Pumps and Multi-Stage Preconcentrators, J Micromech Microeng 24(6) (2014), 980-990.

[49] J.H. Sun, F.Y. Guan, X.F. Zhu, Z.W. Ning, T.J. Ma, J.H. Liu, T. Deng, Micro-Fabricated Packed Gas Chromatography Column Based on Laser Etching Technology, J Chromatogr A 1429 (2016) 311-316.

[50] N.V. Toan, M. Toda, T. Ono, An Investigation of Processes for Glass Micromachining, Micromachines-Basel 7(51) (2016), 1-12.

[51] M.Z. Charles S. Henry, S. M. Lunte, M. Kim, H. Bau and J. J. Santiago Ceramic Microchips for Capillary Electrophoresis–Electrochemistry, Analytical Communications 36 (1999) 305-307.

[52] K.A.Peterson, K.D.Patel, C.K.Ho, S.B.Rhode, .C.D.Nordquist, C.A.Walker, B.D.Wroblewski, M. Okandan, Novel Microsystem Applications with New Techniques in Low-Temperature Co-Fired Ceramics, Int J of Appl Ceramic Tech 2(5) (2005) 345-363.

[53] D.R.Adkins, P. Lewis, Folded Passage Gas Chromatography Column, Patent ApplicationUS 2011/0226040 A1, (2010).

[54] L.S. Ettre, Evolutions of Capillary Columns for Gas Chromatography, LCGC, (2001), 48-59.

[55] P.R.L.R. Wheeler, Non-Planar Microfabricated Gas Chromatography Column, US Patent,US7273517B1 (2005).

[56] Defiant Technologies.http://www.defiant-tech.com/gasmodules.php

[57] M.L. Lee, A. Ghosh, A.R. Foster, C.R. Vilorio, J.C. Johnson, X. Xie, L.M. Patil, L.T. Tolley, HD. Tolley, A.R. Hawkins, B.D.Iverson, Novel Column Technologies for Portable Capillary Chromatography, Oral Presentation, ISCC, GCxGC Riva, Italy, (2018).

[58] S.I. MacNaughton, S. Sonkusale, Gas Analysis System on Chip With Integrated Diverse Nanomaterial Sensor Array, IEEE Sens J 15(6) (2015) 3500-3506.

[59] S. MacNaughton, Programmable Integration of Heterogeneous Nanomaterial Arrays onto Arbitrary Substrates with Applications in Gas Sensing, ProQuest Dissertations and Theses, Tufts University, USA, (2014).